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13. ABSTRACT (Maximum 200 words)
Experimental and theoretical investigations address nonlinear dynamics and complexity in basic nonlinear optical interactions. Notably contributions include (a) first demonstration of chaotic dynamics of stimulated Brillouin scattering (SBS) confirmed through the latest dynamical measurement tools (b) stochastic effects shown to dominate dynamics for cavityless operation but to be suppressed for SBS with feedback (c) first generalised treatment of stimulated scattering in which deterministic dynamics and chaos are shown to be inherent features of behaviour consistent with experimental findings (d) first evidence of patterns, singularities and turbulance in SBS through multi transverse mode interactions (e) generalised analysis of transverse patterns and instabilities of diffraction-diffusion type systems in nonlinear optics - ongoing (f) low frequency (MHz) dynamics and chaos in diode lasers with feedback and in NdYAG modulated lasers - ongoing (g) control of chaos in diode lasers and development of new all optical control algorithms - ongoing (h) lasing without inversion in V systems and (i) new approach to the theory of radiation matter interactions for arbitrary field strength.

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DONALD R. ERBSCHLOE, Lt Col, USAF
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Commander

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THIRD AND FINAL TECHNICAL REPORT

Grant No. AFOSR-91-0286

Dynamical Instabilities, Chaos, and Spatial Complexity in Fundamental Nonlinear Optical Interaction

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Preamble:

The specified three year programme concerned experimental investigations and mathematical modelling of the dynamics and spatial temporal complexity of basic nonlinear optical processes. Consideration was given to systems both with and without external feedback, the latter being of special interest in investigating the generic nature of such behaviour

The programme, based at Heriot-Watt University, utilized the hardware and software of a comprehensive laser/computer laboratory comprising Nd:YAG and Argon ion single and multimode c.w lasers, diode lasers, fibre optics laboratory and full diagnostic facilities providing high speed data acquisition facilities plus a powerful dedicated research computer for real time analysis.

The specific areas of research (as detailed in the proposal) included:

(a) Nonlinear dynamics and spatial complexity of stimulated scattering with and without cavity feedback.

(b) Implications of nonlinear dynamical behaviour to Brillouin and Raman lasers.

(c) Influence of stochastic processes (spontaneous scattering) on deterministic behaviour.

(d) Nonlinear dynamics arising from nonlinear refraction alone (Ikeda type) and in the presence of stimulated scattering etc.

Experimental investigations of (a)-(d) to use optical fibre systems, facilitating cw conditions of operation and allowing plane wave analysis.

(e) Extension of the above from single mode to multimode fibres, particularly in regard to spatio-temporal complexity.

Investigations in the above areas have been largely completed and as detailed below have led to substantial original contributions to the field. During the period of this contract investigations have also been extended into other timely areas which include

(f) Nonlinear dynamics and chaos of diode lasers.

(g) Control of chaos.

(h) Lasing without inversion in V systems.

(i) Theory of radiation-matter interactions for arbitrary field strength.

A resume of the results of these investigations are given below.

Many aspects of the above work in particular (e,f,g) are ongoing and continue to benefit from strong collaborations with colleagues in the Nonlinear Optics Section of Phillips Laboratory. Indeed the exchange visits between the groups of Phillips and Heriot-Watt during this contract proved of considerable value for exchange of ideas and the development of timely research in areas of mutual interest in the above fields.

Resumé of results:

(1) Nonlinear Dynamics and Chaos of Stimulated scattering

Experimental:

i) First evidence of rich aperiodic Stokes emission of stimulated Brillouin scattering (SBS) shown to be prevalent over all operating conditions. No evidence of dc emission [1]

Single mode optical fibre was used to generate SBS under cw single mode pump conditions (both 514nm from Argon Ion and 1.06μm from Nd:YAG) resulting in first order Stokes emission only. Both the transmitted pump and back scattered SBS were found to exhibit aperiodic behaviour under all operating conditions investigated, including those close to the threshold for SBS; the SBS exhibiting massive instabilities with modulation depths ~100%.

ii) With cavity feedback, a dramatic modification of SBS dynamics to sustained and bursting modes of quasi periodic behaviour [2,3]. The generality of these observations at 514nm has been established for all fibre lengths investigated (from 38 to 300 metres) and for all launch powers typically 0.1-3 Watts in 200 m fibre) using both the natural reflectivity of the fibre ends and also external mirror systems.

iii) First demonstration of chaotic dynamics of SBS, confirmed through the latest dynamical measurement tools [4].

Extension of investigations in (ii) using cw pumping at 1.06μm for which fibre losses are substantially reduced established dynamical features of distinct form, notably the onset of limit cycles from the threshold for SBS, evolving to deterministic chaos through a two frequency route [4]. In distinguishing stochastic from deterministic chaotic behaviour it has been recently recognised that more comprehensive measurement techniques are essential to augment the usual correlation dimension algorithm of Grassburger and Proccacia. Accordingly in this work these latest tools are deployed to characterise the dynamical behaviour of the Stokes emission. In particular correlation dimension analysis has been applied to and compared with those of the time difference and phase randomised

(surrogate) sets of the aperiodic time series. Results show the dynamics of the emission to be highly deterministic low dimensional chaos [4].

iv) Stochastic effects shown to dominate deterministic dynamics for cavityless operation while for SBS with feedback, even weak, their effect is only felt at threshold [4,6].

The influence of noise on the dynamics of nonlinear systems is an issue of current interest particularly in regard to systems in which signals are initiated from stochastic effects. Stimulated Brillouin scattering is a paradigm of such interactions. The above investigations (iii) have further established that the dynamics are in fact noise dominated only for weak pumping near or at the threshold for SBS. In contrast in the absence of feedback the deterministic dynamics is largely suppressed or masked by stochasticity for all operating conditions. As above, standard correlation dimension analyses has been augmented with the new measurement procedures in quantifying and distinguishing the dynamical behaviour.

Theory:

v) First generalised treatment of stimulated scattering in which, deterministic dynamics and chaos are shown to be inherent features of behaviour [5].

Our analysis is based on a reasonably complete description of these interactions in which account is taken of the gain of the scattering processes as well as the nonlinear refraction induced by the pump and scattered signals. For clarity we restrict our attention to the common case of counter-propagating pump and stimulated scattered signals. Dynamical instabilities are found to be generic to these interactions and to prevail over remarkably extensive regions of parameter space which may extend down to the threshold for stimulated scattering. Within these regions we identify various forms of dynamical behaviour and in particular establish quasi-periodic routes to chaos. Our findings contrast dramatically with those of conventional descriptions which are truncated by omitting the contributions of nonlinear dispersion and lead to only stable d.c solutions.

vi) Extension of the analysis to include external feedback confirm the essential role of nonlinear refraction to the dynamical behaviour [2,6,8].

Theoretical results show the Stokes signal to exhibit huge sustained or random bursts of quasiperiodic emission. Comprehensive comparisons with experimental findings as detailed in (ii) give good agreement regarding both the dynamical features of the Stokes

emission and their dependence on the physical control parameters, e.g., pump power, cavity reflectivity, and fiber length.

vii) Inclusion of spontaneous emission, as a source term in our analysis has established that the deterministic dynamics and chaos of fundamental SBS is suppressed by noise while for SBS with feedback, even weak, determinism dominates giving rise to rich oscillatory instabilities and chaos as experimentally observed [6,8].

This analysis further confirms the prevalence of stochasticity in the vicinity of the SBS threshold. In this work the various dynamical measurement techniques described above have been utilised in quantifying the dynamical behaviour.

2) Transverse patterns and Complexity in Stimulated Scattering.

Our investigations have been extended to consider pattern formations and spatio-temporal complexity in these phenomena through multi-mode interaction. This work is motivated by more general issues of spatio-temporal complexity in optical open flow systems, a new area in the field of nonlinear dynamics. Significant findings of this work include:

Experimental:

viii) First evidence of patterns, phase singularities and turbulent behaviour in stimulated scattering [7].

SBS was generated in multimode optical fibres, pumped by a stabilised single frequency Argon ion laser. Various pattern formations were observed in the transverse field of the SBS, both those arising from fundamental modes of the fibre and their nonlinear combinations. Changes in the formations of the patterns in the presence of feedback were mediated by abrupt symmetry breaking, induced by the creation and annihilation of phase singularities, the motions of which sustained the dynamical behaviour. The dynamics in local regions of the transverse fields were periodic or aperiodic; characterisation of the latter providing evidence of low dimensional chaotic behaviour. The spatial correlation in the transverse domain was found to decrease dramatically with increase in complexity of the patterns.

Theoretical:

ix) Treatment of transverse patterns through multi-mode nonlinear coupling in guided (open flow) media through stimulated scattering.

Towards understanding the phenomena we observe we have extended our theory to address coupled mode theory of SBS in which the physical effects of electrostriction and nonlinear refraction are accounted for. Results, so far for the simplest case of two mode coupling in the presence of feedback, confirm the emergence of dynamic pattern formations in the transverse field of the SBS signals, the dynamics of which is chaotic though on a much faster time scale than in experiment [8].

3) Transverse patterns and Complexity of Diffraction-Diffusion Type Systems.

These investigations, at the present theoretical, consider pattern formations and spatio-temporal complexity through multi transverse multimode interactions in diffraction-diffusion tyre systems both open (unidirectional) and closed (feedback) systems.

x) Transverse patterns through multimode nonlinear coupling in guided (open flow) media through nonlinear refraction.

Here we establish nonlinear coupling instabilities for co-propagating multi mode beam interactions. The coupling considered in this Hamiltonian system arises from the optical Kerr effect and exists among beams that belong to different mode families in optical guided configurations such as multimode fibers. The amplitude and power of each of the beams are found to be spatially unstable and chaotic for four-beam coupling and spatially oscillatory for two-beam interactions dependent on launch conditions [9,10]. Here experiments are currently under way in low bi 2 mode fibre.

(xi) Generalised approach in describing transverse patterns and instabilities of diffraction-diffusion type systems in nonlinear optics [11].

A generalised approach is developed to describe pattern formations in "2+1" systems in their most general form, referred to as diffraction-diffusion type equations, and through this provide a framework for its application to specific pattern forming systems. In this approach the Ginzburg-Landau equation is derived from multiple scales analysis in which the coefficients are determined from relatively straightforward scalar products related to physical parameters through which the relevant features of bifurcation and

pattern formation are more readily revealed. Through this treatment we identify five distinct pattern forming regions and the conditions for their transitions, dependent on the quadratic and cubic terms in the nonlinear expansion. As illustration, we apply this general theory to a thin slice Kerr ring cavity system in a more generalised form and show that pattern formations are altered by the inclusion of diffusion and finite response of the medium, leading to new stable honeycomb patterns for focusing media and further the inclusion of diffusion may lead to a hexagon-roll transition.

4) The investigations detailed below and that of Sect. (xi) above were undertaken within the period of the contract but are outwith the programme of specific research detailed within the original proposal. They are included as they are of special relevance to current activities of Phillips Laboratory and have benefited from interaction with colleagues at Phillips over this period.

xii) Nonlinear Dynamical Chaos in Diode Lasers.

Experimental investigations have established generic low frequency (~ MHz) dynamic and chaotic behaviour from diode laser in the presence of external feedback to be prevalent to their operation, persisting from the first lasing threshold and only under conditions of high current (gain) is the emission stable (d.c). Quasi periodic scenarios are established as common precursors to chaos in a broad range of these systems. Ongoing investigations are quantitative characterisation and theoretical modelling of these new dynamical phenomena.

(xii) Control of Chaos.

Investigations of the last year have increasingly focused this area both through theory and experiment. Systems currently being addressed are diode lasers, a Nd:YAG c.w laser with intracavity acousto optic modulation and various nonlinear electronic circuit systems.

The control algorithm of continuous feedback (K. Pyragos, Phys. Lett. A170, 421, 1992) and the recent extension of this (J. Socolar et al, Phys. Rev. E, 50, 324 1994) along with OPF are currently being applied to chaotic electronic circuits, as a basis for quantitative evaluations and to single element laser diode systems with external feedback. The objectives of this work are:

(a) Control and tracking of chaos in diode lasers.

(b) Synchronisation of chaos in diode laser arrays.

(c) Control and tracking of chaos in diode arrays.

(d) Application of all-optical control algorithms to chaotic diode laser and chaotic modulated Nd:YAG systems; the latter providing an ideal test bed for evaluation of control.

(e) Investigation of control of spatial temporal instabilities and chaos in wide area diode lasers and multi transverse mode Nd:YAG systems.

To date results have established control and tracking with both the electronic and diode laser systems though the operational features of continuous feedback are in practice found to differ substantially from predicted behaviour; an area of current investigation.

In parallel theoretical work in this area we have proposed and demonstrated theoretically a new all optical method of continuous interference feedback for control of chaotic behaviour [12]. The algorithm exploits the advantages of the CSC scheme, benefits from the simplicity of all optical implementation and, through the high speed optical circuits, accesses control of chaos in optics, both lasers and devices, in the high frequency range. This control procedure may be readily implemented using standard interferometric techniques and should prove of special value in the control of systems which exhibit fast dynamical behaviour, such as diode lasers, requiring signal differencing on time scales of pico- to nano-seconds.

(xiii) Lasing without inversion in a V system [13,14].

In recent years many papers have been devoted to the study of lasing (or amplification) without population inversion in multilevel systems. For three-level A schemes this phenomena arises from either phase-dependent quantum interference (or trapping effects) or electromagnetically induced interference in lifetime broadened systems, two distinguishable mechanisms. While for both systems a coherent pump is required to drive the systems, additional pumps, coherent or incoherent, are also required either for coherent coupling or two of the (closely spaced) levels or for redistribution of the thermal population, respectively.

In this work we consider lasering without inversion in a V system driven by a *single* pump field, the simplest system considered to date in terms of both the level scheme and its interaction with the optical field [13,14]. Here the role of the single optical field is both to drive the system and more significantly, to modify the states for which it interacts. the

latter, through state splitting, forms a coherently coupled pair of states which can result in a trapped state, similar to that formed by a degenerate or near-degenerate pair of real ground-state levels in the more familiar schemes normally considered. This is the underlying physical mechanism responsible for lasing without inversion in the B system, the conditions of which are shown to depend mainly on the relaxation rates and photon degeneracy parameters of the system.

(xiv) New approach to the theory of radiation-matter interactions for arbitrary field strength [15].

In this work we have developed a new approach to describe radiation-matter interactions that extends conventional perturbation theory to accommodate arbitrary field strength by introducing the concept of self-regulated partitioning of the interaction Hamiltonian. The treatment gives a clear physical insight into field-induced splitting of the states, called here partially dressed states, and also accounts for the transition of energy between the states. In general these states are characterised by the strength and form of the field-matter interaction and determined by comparison with density-matrix analysis. Using these states as base states, this theory allows for a perturbation-expansion analysis for arbitrary interaction strength. This treatment provides an analytic basis for describing multilevel radiation interactions, and by way of example we consider its application to third-harmonic generation.

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